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Biosynthesis And Characterization Of Co_3O_4 Nanoparticle For Enhanced Photocatalytic Activities

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ABSTRACT

With rising concerns about environmental pollution and the drawbacks of traditional chemical synthesis methods, the synthesis of environmentally friendly semiconductor nanomaterials has garnered significant interest. In the present study, the preparation of Cobalt oxide (Co_3O_4) nanoparticles was carried out by using a biological (green) synthesis route using bacterial metabolites as reducing and stabilizing agents. The synthesized nanoparticles were characterized in terms of their structural, morphological, elemental and optical properties by using X-ray diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), High-Resolution Scanning Electron Microscopy (HR-SEM), Energy Dispersive X-ray Spectroscopy (EDX) and UV–Vis spectroscopy. The XRD results showed that large amounts of highly crystalline (cubic-phase) Co_3O_4 nanoparticles with an average crystallite size of ~19.29 nm were formed. The SEM micrographs showed mostly spherical shapes of nanoparticles with relatively uniform morphology and the EDX spectra demonstrated that the cobalt nanoparticles were free of elemental impurities and the oxygen was free of impurities except for carbon. FTIR analysis confirmed the characteristic bands of the vibrations related to the formation of cobalt oxide. The optical band gaps were found to be 1.75 eV and 2.46 eV by a UV–Visible spectroscopy technique, respectively for the NCAP and NCG, which showed that these materials are semiconductors and efficient absorbers of visible light. The biosynthesized nanoparticles showed a higher photocatalytic activity than the conventionally synthesized Co nanoparticles, thereby proving their potential for environmental remediation applications. The results showed that biological synthesis is a cost-effective, eco-friendly, and sustainable method to synthesize highly active CO_3O_4 nanoparticles that have potential applications in wastewater treatment, environmental purification, and photocatalytic degradation of organic contaminants.

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Keywords— Biosynthesis of Cobalt oxide nanoparticles: Co_3O_4, Green synthesis, Photocatalysis, Nanomaterials and environmental remediation.

Introduction

The ability to manipulate matter at the nanoscale (1-100 nm) has led to the emergence of nanotechnology as one of the fastest growing scientific disciplines with materials showing properties that are distinct from their bulk counterparts in physical, chemical, electrical, optical, and catalytic properties. Nanomaterials are interesting because they have extremely high surface to volume ratios which enhance surface reactivity, charge transport, and tuneable optical properties, making them promising for use in catalysis, remediation, medicine, sensing, and energy conversion.

Transition metal oxides (TMOs) are semiconductor nanomaterials that have a high catalytic efficiency, chemical stability, and have relatively low production costs, making them of great scientific interest. Cobalt oxide Co_3O_4 is a mixed valence semiconductor of p-type, which has a cubic spinel crystal structure and has attracted researchers' interest as a multifunctional nanomaterial with remarkable electrochemical, magnetic, catalytic, optical properties. Co_3O_4 is a spinel structure that allows the simultaneous presence of both Co^{2+} and Co^{3+} ions in the crystal lattice, which creates a large number of active sites that can facilitate oxidizing–reduction reactions, making this material very attractive for photocatalysis, lithium-ion batteries, gas sensors, supercapacitors, and water purification technologies.

Continuous discharge of industrial dyes and toxic organic pollutants into water bodies is one of the biggest environmental issues that are faced by modern society. Typical wastewater treatment processes are expensive to operate, fail to completely remove contaminants, and produce secondary pollutants. Semiconductor photocatalysis has thus become an eco-friendly approach that can oxidize toxic organic pollutants to non-toxic components using light to break them down into harmless end products. Crystallinity, particle size, morphology, surface and optical band-gap energy are all important factors in determining the photocatalytic efficiency of semiconductor nanoparticles and consequently need to be controlled in the synthesis procedures.

Previously, Physical and Chemical methods including sol–gel processing, hydrothermal synthesis, co-precipitation, thermal decomposition and chemical vapor deposition have been used to prepare Co_3O_4 nanoparticles. These methods provide control over the properties of the nanoparticles, but often require expensive equipment, high temperature, toxic reducing agents, toxic solvents, and considerable energy. In addition, these methods can produce unwanted chemicals as a byproduct of the synthesis, which can have toxic effects on the environment and living organisms, affecting their sustainability.

Recently, an environmentally friendly alternative to the production of nanoparticles, namely green or biological synthesis, has come into the spotlight. Biomolecules present in biological systems (plants, fungi, algae and microorganisms) are able to reduce metal ions, and stabilize formed nanoparticles without using toxic chemicals. The microbial metabolites provide several benefits such as decreased production costs, less environment impact, better biocompatibility, and the control of the nanoparticles morphology and stability. Thus, there is a great interest in the synthesis of nanoparticles via biological pathways for biomedical, catalytic, and environmental applications.

Although the synthesized nanomaterials in biological way is a growing research interest, very

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few works have been focused on the structural, optical and photocatalytic properties of biosynthesized Co_3O_4 nanoparticles. In particular, extensive characterization techniques using crystallographic, morphological, elemental, and optical analyses have been lacking and comparative evaluations of photocatalytic performance have been under-explored when compared to photocatalysts synthesized using more conventional techniques.

In view of this, the current study was designed to synthesize nanoparticles of Co_3O_4 by an eco-friendly biological approach and to thoroughly explore the physicochemical characteristics of the synthesized nanoparticles using different techniques including X-ray diffraction (XRD), High-Resolution Scanning Electron Microscopy (HR-SEM), Energy Dispersive X-ray Spectroscopy (EDX), Fourier Transform Infrared Spectroscopy (FTIR), and UV–Visible spectroscopy. In addition, the photocatalytic activity of the biosynthesized nanoparticles is assessed for possible use in environmental remediation. The environmentally friendly synthesis method used in this work is expected to be a promising method in the production of highly crystalline Co_3O_4 nanoparticles for wastewater treatment applications and other environmental applications with high photocatalytic activities.

Literature Review

Cobalt Oxide Nanoparticles

The use of nanotechnology has become one of the most promising areas of materials sciences with the development of materials with structural properties distinct from those of bulk materials, and with unique optical, electrical and catalytic properties. The dimensions of the nanoparticles are usually in the range of 1–100 nm, which means that they have an extremely high surface-to-volume ratio, which in turn improves the reactivity of the chemical and the adsorption capacity and catalytic activity. The properties have found many applications in environmental cleanup, energy storage systems, catalysis, biomedical engineering, and sensing technologies.

Cobalt oxide (Co_3O_4) is the most studied transition metal oxide, which has a mixed valence spinel structure with both Co^{2+} and Co3+ ions. This crystal chemistry generates excellent redox activity, high thermal stability, resistance to chemicals, magnetism and semiconductor properties. Due to these properties, Co_3O_4 nanoparticles are regarded as promising materials in lithium-ion batteries, supercapacitors, gas sensors, heterogeneous catalysts, antimicrobial materials and for photocatalytic degradation of organic pollutants. They also have a relatively small band-gap energy which also allows them to efficiently absorb visible light, making them good photocatalysts for wastewater treatment.

Compared to bulk cobalt oxide, nanoscale Co_3O_4 shows catalytic activity that is much higher as a result of increased number of active surface sites and reduced diffusive length for photogenerated electrons and holes. Thus, the recombination of electron–hole is decreased, which is beneficial for photocatalytic efficiency. The crystallinity, the morphology, the particle size, the porosity, and the surface chemistry are all important parameters that are affected by the synthesis route used, and which determine the performance of the Co_3O_4 nanoparticles.

The synthesis of Co_3O_4 nanoparticles using the green route.Green synthesis of Co_3O_4 nanoparticles

Numerous techniques for the synthesis of cobalt oxide nanoparticles are available, such as hydrothermal processing, sol–gel synthesis, co-precipitation, chemical vapor deposition, thermal decomposition, combustion synthesis, and microemulsion methods. The methods which use these principles yield nanoparticles having controlled physicochemical properties,

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but they often involve high temperature, flammable reducing agents, toxic solvents and expensive equipment. Furthermore, they are not environmentally sustainable because it produces chemical wastes and requires a lot of energy.

In order to overcome these drawbacks, a green alternative, green synthesis, is emerging. Biological synthesis uses plants, bacteria, fungi, algae, or naturally occurring biomolecules as reducing and stabilizing agents, eliminating the use of hazardous chemicals and reducing the amount of energy used. This method is in line with principles of green chemistry as it reduces environmental impact and yields environmentally friendly nanomaterials under mild conditions.

The use of microbial synthesis is especially appealing, as bacteria can synthesize enzymes, proteins, amino acids and extracellular metabolites that can reduce metal ions and stabilize newly formed nanoparticles. These biomolecules also affect the shape, crystallinity and dispersion of nanoparticles, enabling the creation of highly stable nanoparticles with precise physicochemical properties. It has been recently reported that the nanoparticles of Co_3O_4 prepared by biological process can be comparable and even better than those in the traditional chemical process in terms of photocatalytic performance with less environmental hazard.

The rise in the number of publications over the last decade signals the rising interest in the synthesis strategies that are more sustainable. Co_3O_4 nanoparticles have been synthesized using plant extracts, bacterial culture, fungal metabolites, starch, sucrose, gelatin, etc. which are all renewable biological resources, and researchers are achieving good results. All these studies frequently show that green synthesis results in better biocompatibility, lower toxicity and higher environmental compatibility, so green synthesis is a significant research field in nanotechnology.

Characterization of Co_3O_4 Nanoparticles

Synthesized nanoparticles must be characterized comprehensively to understand the physicochemical properties of these particles and to define the structure–activity relationships. X-ray diffraction (XRD) is a common method used to identify the crystal structure, crystallite size, lattice parameters, and phase purity. The successful formation of Co_3O_4 is confirmed by the presence of diffraction peaks corresponding to the cubic spinel structure, and crystallite size can be determined from the Debye–Scherrer equation.

Scanning electron microscopy (SEM) is generally used to study surface morphology and particle distribution while energy-dispersive X-ray spectroscopy (EDX) is used to obtain the elemental composition, both qualitatively and quantitatively. The functional groups that could be involved in the process of formation and stabilization of nanoparticles are identified using Fourier transform infrared spectroscopy (FTIR) and the optical absorption spectrum is estimated by measurement using UV–Visible spectroscopy. Combined, these complementary analytical procedures allow for a complete understanding of crystallinity, morphology, purity and optical properties of nanoparticles.

The photocatalytic applications of Co_3O_4 nanoparticles

Dye effluents from industries are a significant environmental problem as many synthetic dyes are resistant to biodegradation, are highly chemically stable and are toxic. Therefore, semiconductor photocatalysis has been developed as an effective advanced oxidation process (AOP) that can be used to degrade these pollutants into less harmful products by generating reactive oxygen species (ROS) upon light irradiation.

The Co_3O_4 nanoparticles are highly promising as photocatalysts because of their low band gap,

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having multiple oxidation states, and the ideal charge transfer characteristics. With the irradiation, electrons are raised from the valence band to the conduction band and the hole is left with a positive charge, which can be involved in the oxidation reaction. The hydroxyl radicals and superoxide radicals generated in this way destroy organic dye molecules, leading eventually to the formation of carbon dioxide, water and other harmless compounds. The efficiency of this process is dependent on the crystallinity of the semiconductor, the particle size and surface area, the morphology, and the reduction of electron–hole recombination.

The recent investigations revealed that the biosynthesized Co_3O_4 nanoparticles have high photocatalytic efficiency in degradation of methylene blue, methyl orange, rhodamine B and other organic dyes. The small crystallite size, high surface area and the biologically generated functional groups at the surface, which help to bind dyes and separate charges are typically cited as the reasons for the enhanced photocatalytic activity. The results indicate that the green synthesized Co_3O_4 nanoparticles could be viable catalysts for wastewater treatment and environmental clean-up applications in the future.

Research Gap

Despite significant advances, there are still some challenges in the synthesis and application of the Co_3O_4 nanoparticles. The majority of studies reported in the literature have been performed using traditional chemical synthesis techniques based on the use of toxic chemicals, high temperatures and complicated synthesis procedures. Furthermore, fewer studies have focused on microbial mediated biosynthesis and at the same time studied the structural, morphological, optical and photocatalytic properties by combining a number of characterization techniques. However, comprehensive investigations of the composition of materials, based on XRD, SEM, EDX, FTIR, UV–Visible spectroscopy, and photocatalytic performance analysis are still relatively scarce.

In this context, the present work aims to fill these gaps using a bacterial mediated green synthesis method for the preparation of Co_3O_4 nanoparticles, with detailed physicochemical characterization, and an evaluation of the efficiency of their photocatalytic activity. This work adds to the growing body of knowledge concerning the relationship of biosynthesis, properties of the resulting nanoparticles, and their photocatalytic performance, and also advanced the development of environmentally sustainable and cost-effective nanomaterials for wastewater treatment.

Materials and Methods

Materials

All the experimental work was carried out using analytical grade chemicals which were not further purified. The cobalt precursor used was cobalt sulfate heptahydrate ($CoSO_4 \cdot 7H_2O$) and the bacterial growth medium used was lysogeny broth (LB) medium, which contains tryptone, yeast extract and sodium chloride. All solution preparation was done using distilled water, to prevent contamination of the solutions during the synthesis of the nanoparticles.

Biosynthesis of Co_3O_4 Nanoparticles

Bacterial metabolites were used as reducing and stabilizing agents for the fabrication of cobalt oxide nanoparticles via a green route. LB medium was first made by dissolving sodium chloride, tryptone and yeast extract in distilled water and making it sterile. The prepared medium was used for the inoculation of a bacterial colony and incubated overnight to allow for good bacterial growth. After incubation, the culture was centrifuged at 6000 rpm for 12 min to remove the extracellular metabolites. Supernatant (biologically active compounds) was

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carefully collected and bacterial pellet discarded.

Aqueous solution of cobalt sulfate heptahydrate was then made and then equal volume of that solution was mixed with the bacterial supernatant. The reaction mixture was placed in sterile Falcon tubes and heated to 100°C for 20 min, where during the process cobalt ions were reduced, forming cobalt oxide nanoparticles. The suspension was then centrifuged at 13500 rpm for 15 min to collect the nanoparticles. The collected precipitate was washed with distilled water and later was dried in a laboratory oven at 100°C for 2 h. Finally the dried material was calcined in a muffle furnace to yield the crystalline CoO nanoparticles for physicochemical characterization.

Characterization Techniques

The structural and morphological, elemental and optical properties of the biosynthesized nanoparticles were characterized through complementary analytical techniques.

X-ray Diffraction (XRD)

X-ray diffraction (XRD) was used to investigate the crystalline structure and phase purity of synthesized Co_3O_4 nanoparticles. The diffraction patterns were collected over an appropriate range of 2θ measured by Cu-Kα radiation. The diffraction peaks obtained were matched with the standard crystallographic data to ensure the formation of the cubic spinel Co_3O_4 phase. The Debye – Scherrer equation was applied to estimate the average crystallite size:

D=Kλβcos⁡θD=\frac{K\lambda}{\beta\cos\theta}D=βcosθKλ

Where the crystallite size, D, the shape factor K (0.9), wavelength of X-ray λ, the half width at maximum intensity β, and the Bragg diffraction angle θ.

Scanning Electron Microscopy (SEM)

The synthesized nanoparticles were analyzed by scanning electron microscopy (SEM) to study their surface morphology and particle distribution. The samples were placed on conductive stubs and then investigated under high vacuum conditions. The particle size, shape, texture and size of agglomeration were evaluated using SEM images.

The 2.3.3 Energy Dispersive X-ray Spectroscopy (EDX) will examine the chemical composition of the sample.

The elemental composition was analyzed by energy dispersive X-ray spectroscopy (EDX) equipped with SEM instrument. The EDX spectra confirmed the presence of cobalt and oxygen and have been used to measure the purity of the synthesised nanoparticles by determining potential contaminants.

Fourier Transform Infrared Spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) analysis was used to identify the functional groups that participate in the synthesis and stabilization of nanoparticles. The spectra were collected in the mid-infrared region (400–4000 cm^{-1}), which enabled the identification of vibrations of stretching bonds of metal–oxygen typical of cobalt oxide, as well as the biomolecules that were bound to the surface of the nanoparticle.

UV–Visible Spectroscopy

The synthesized nanoparticles were analysed by UV–Visible spectroscopy for their optical absorption properties. Co_3O_4 nanoparticles' optical response was determined by measuring their absorption spectra in the ultraviolet and visible ranges of the electromagnetic spectrum. The absorption data was used to estimate the optical band-gap energy by the Tauc relation and this revealed the semiconductor nature of the synthesized material.

Photocatalytic Evaluation

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The photocatalytic activity of the biosynthesized Co_3O_4 nanoparticles was evaluated using a model organic dye under light illumination. Concentration of the dye was measured at fixed time intervals by UV–Visible spectroscopy. The photocatalytic degradation efficiency was computed by using the following equation:

Degradation (%)=C0−CtC0×100\text{Degradation (\%)}=\frac{C_0-C_t}{C_0}\times100Degradation (%)=C0C0−Ct×100

where C_0 is the initial dye concentration and C_t is the concentration of dye after the irradiation time t. Comparative analysis was carried out to compare the catalytic activity of the biosynthesized nanoparticles and conventionally synthesized cobalt oxide nanoparticles.

Statistical Analysis

The experimental measurements were all made under the same laboratory conditions to assure repeatability. Standard instrument software was used to analyze the data obtained from the characterization techniques such as XRD, SEM, EDX, FTIR and UV-visible spectroscopy. The crystallite size, elemental composition and optical band-gap values were calculated and were interpreted in reference to the previously published studies to judge the quality and the photocatalytic activity of biosynthesized Co_3O_4 nanoparticles.

Results and Discussion

X-RAY DIFFRACTION ANALYSIS (XRD)

The crystal structure was determined by X-ray diffraction (XRD) analysis.The crystal structure was characterized by X-ray diffraction (XRD).

The crystalline structure and phase purity of biosynthesized Co_3O_4 nanoparticles was analyzed with XRD. The diffraction pattern exhibited well-defined diffraction peaks at 2θ values of 18.57°, 31.46°, 36.26°, 38.47°, 44.54°, 55.74°, 59.48°, and 65.66°, corresponding to the (111), (220), (311), (222), (400), (422), (511), and (440) crystallographic planes of cubic spinel Co_3O_4 (JCPDS Card No. 42-1467). The purity of the synthesized single-phase high crystallographic purity cobalt oxide nanostructure was confirmed by the absence of impurity peaks.

The diffraction peaks are sharp, suggesting good crystallinity, which indicates that the precursor is a good biosynthesized material and the calcination procedure was effective in converting it to crystalline Co3O4 nanoparticles. The lattice parameter calculated (8.091 Å) is in close agreement with reported values (about 8.08 Å), which indicates that the required spinel crystal structure has formed.

The average crystallite size calculated by Debye–Scherrer equation was 19.29 nm which was in the nanometer range. The benefits of such a small crystallite size are its ability to increase the specific surface area, expose more catalytically active sites, and reduce the diffusion distance of the photo-generated charge carriers. Thus, it is expected that such particles would result in improved photocatalytic performance than larger crystalline particles.

In conclusion, the XRD analysis confirms that the biological synthesis method was effective in producing highly crystalline, phase pure Co_3O_4 nanoparticles that can be used in photocatalytic applications.

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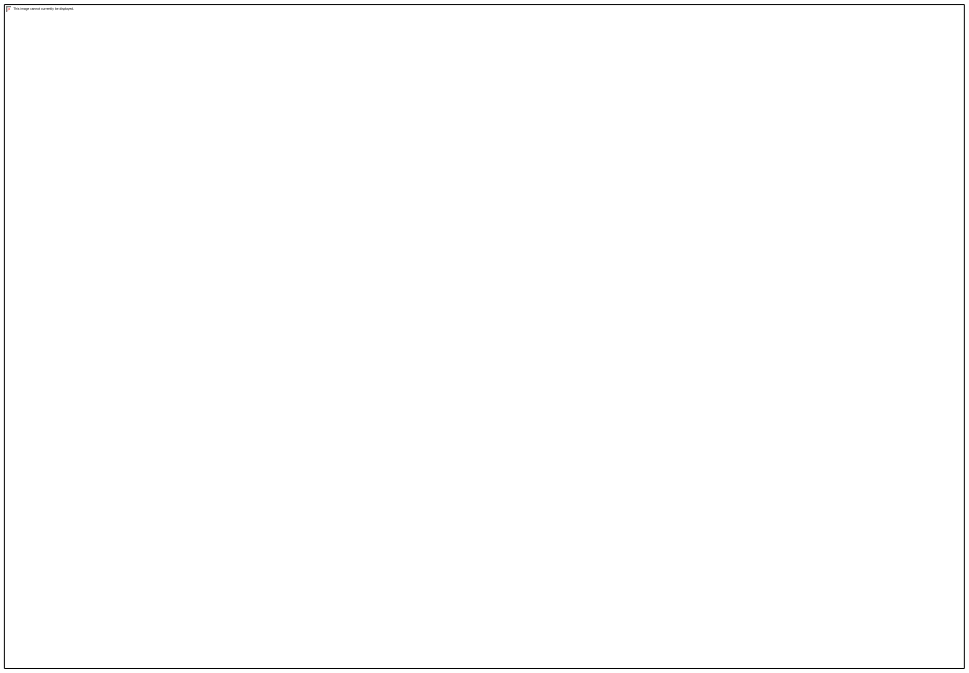

Figure4.1. XRD Spectrum of Co_3O_4 nanoparticles.

The formula in equation 1 was used to get the lattice parameter.

$Sin^2\theta = \lambda^2/4[4/3\ (h^2 + hk + k^2)/a^2 + l^2/c^2]$----------Eq 4.1

Whereθ is the scattering angle,λ is the incidence wavelength (=0.1540 nm), and the Miller indices are h, k, and l. The sample diffraction pattern is found to be 8.091 Å. Yan et al. [80] and Tuwirqi et al. [81] previously reported similar lattice parameter values (a=8.084 Å and a=8.082 Å).

Eq.2, Scherer's formula was used to get the average crystallite size.

$L = 0.89\lambda/\beta \cos\theta$----------Eq 4.2

where L stands for crystallite size, λ X-ray wavelength, θ, Bragg diffraction angle, and β, full breadth at half maximum (FWHM). The sample's average crystallite size was discovered to be 19.29 nm.

SCANNING ELECTRON MICROSCOPY (SEM)

The samples' sem micrographs were validated using a high-resolution transmission electron microscopy (HR-SEM). HR-SEM images of a Co_3O_4 sample are shown in Figure 2. We may deduce from the HR-SEM images that the Co_3O_4 sample's surface morphology resembles that of nanospheres nanoparticles. The micrographs of samples are widely recognized to be affected by sample fabrication, sintering temperatures, reaction rate, lubricants, and other factors. Sem images of fabricated nanoparticles showspherical-like morphology.

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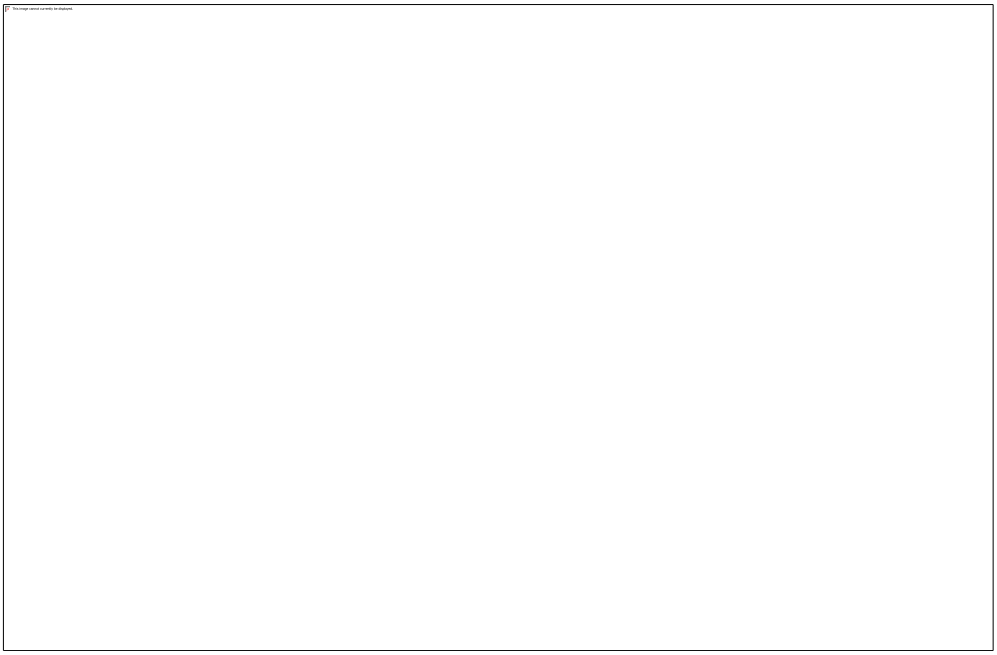

Figure4.2 a and b the SEM images of Co_3O_4 nanoparticles

ENERGY DISPERSIVE X-RAY (EDX) ANALYSIS

Energy-dispersive X-ray analysis (EDX) was used to analyze the chemical purity and chemical compositions of the product, as shown in Fig. 3. The existence of Co and O peaks and with no other diffraction peak in the EDX data indicates the existence of Co and O, implying that the processed sample did not contain any other element contaminants. In addition, a minor gold (Au) signal occurred at 2.1 keV, indicating that the sample had been coated for increased visibility of the surface morphology during the HR-SEM examination.

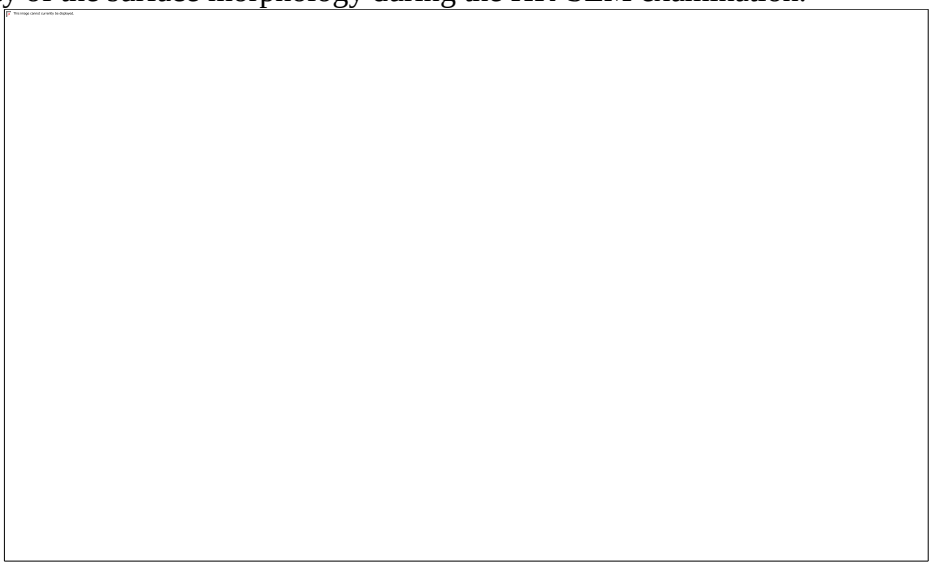

Figure4.3 Elemental composition of cobalt oxide nanoparticles.

FOURIER TRANSFORM INFRARED SPECTROSCOPY (FTIR)

Figure 4 shows the FT-IR spectra of Co_3O_4 nanoparticles. The existence of broadband between

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3200 and 3500 cm1 in Fig. 4 was mostly attributable to the hydroxyl (O–H) stretch mode. The combined band of C–H or O–H stretch was blamed for a weak band that occurred at 2137 cm^{-1}. A strong band at 1646 cm^{-1} also proved the presence of O–H bending vibrations in water molecules. Furthermore, absorption bands between 650 and 850 cm^{-1} were seen in the PL spectra of Co_3O_4 samples, which match the Co–O stretched mode of vibration.

Figure. 4.4 FT-IR Spectra of Co_3O_4 nanoparticles.

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4.5 DIFFUSE REFLECTANCE SPECTROSCOPY (DRS) ANALYSIS.

At room temperature, UV–Visible DRS was used to evaluate the sample's optical characteristics. Co_3O_4 nanoparticles are electron donors that have direct transitions in the visible portion of the spectrum. The Kubelka–Munk (K-M) model may be used to compute the optical band gap (Eg) of spinel Co_3O_4 nanoparticles, and the F(R) value can be obtained by applying the method given in Eq (3).

$$F(R) = (1 - R)^2 /2R \qquad \text{Eq 4.3}$$

The Kubelka–Munk function is F(R), and R is the absorbance. Trying to extrapolate the linear dependence of the plot of $[F(R)h]^2$ versus photon energy as shown in Fig. 5, which exhibits the two optical band gaps (Eg) that can be attributed to $O^{2-}Co^{2+}$ charge transfer and $O^{2-}Co^{3+}$ charge transfer processes, the bandgap can be determined.The computed Eg values of the synthesized Co_3O_4 nanoparticles (1.89 and 2.54 eV) were found to be lower than those published by Farhadi et al. [80] and higher than those reported recently by Yan et al. [82]. Furthermore, the presence of two band gaps with particular specified values demonstrates that the samples are pure P-type semiconductors.

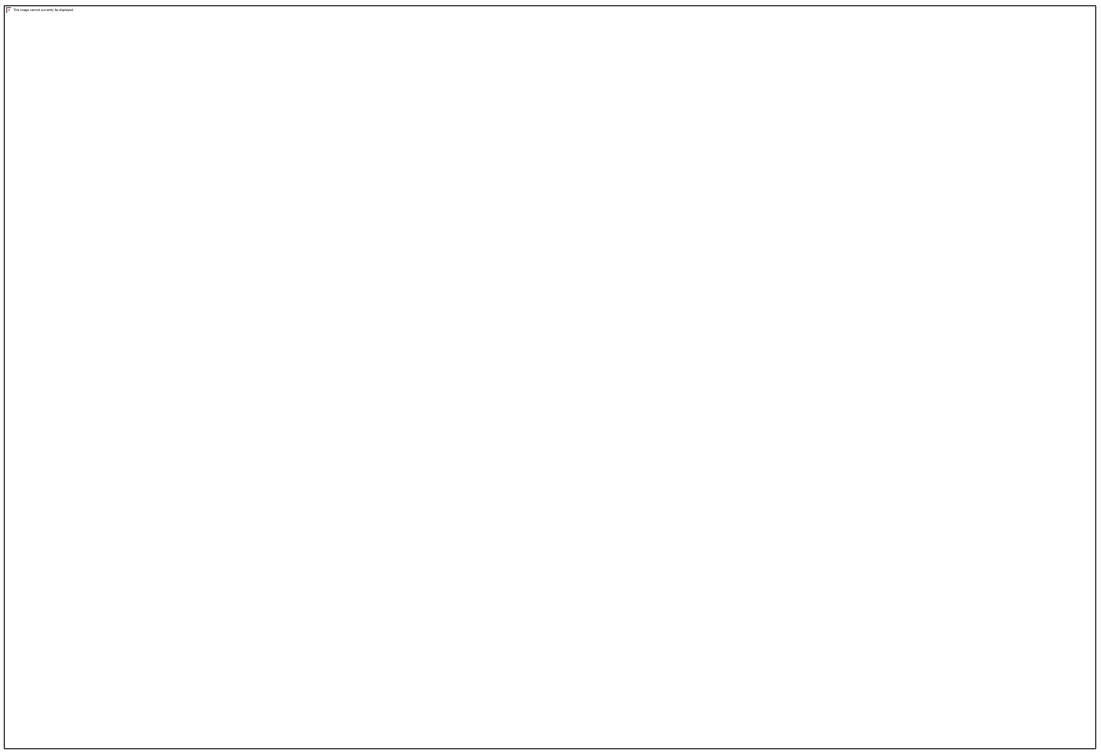

Figure. 4.5UV–Vis DRS Spectra of Co_3O_4 nanoparticles.

4.6 PHOTOCATALYTIC PROPERTIES

Methylene blue, a reactive dye is commonly dye using, textile, wool, and silk. In humans and animals, MB can induce eye burns, cyanosis, skin irritation, vomiting, and diarrhea. The toxicity of the MB dye effluent causes soil microorganisms to die. Because dyes are not easily degradable, it is difficult to remove the MB dye from the effluent.To break down the dyes, a sufficient catalyst is necessary. The crystallinity, size, form, and shapes of nanomaterials have long been thought to be important variables in their photocatalytic activity. We attempted to disclose the relationship between optical and photocatalytic capabilities of Co_3O_4

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nanomaterials in this study, and a series of experiments were carried out with MB dye in an aqueous solution under 365 nm light. The effect of a Co_3O_4 nano-photocatalyst on PCD efficiency was assessed as shown in Fig. 6.

In the presence of the catalyst, regulatory investigations were performed by irradiating the solution with UV radiation (photolysis). The photolysis degradation of MB was found to be 10% less than that of other materials. The photocatalytic activity of single-phase Co_3O_4 nano-photocatalyst, on the other hand, was determined to be 94.61 percent efficient.

The pseudo-first-order rate equation was used to investigate the photo-degradation kinetics of MB employing a Co_3O_4 nano-photocatalyst in the presence of UV light (Eq. 4),

$$\ln (C_t/C_o) = k_1 t \qquad \text{Eq 4.4}$$

where C_o represents the initial concentration (mg/l), C_t represents the concentration (mg/L) at time t, represents the UV light exposure duration, and k_1 represents the first-order rate constant.The overall effect of MB molecule adsorption over catalyst surface proceeded by oxidation using the created hydroxyl radical and direct assault of photo-induced holes can be explained by the higher rate constant attained employing Co_3O_4 catalyst. However, in this work, we discovered that the PCD activity rose as the duration (270 minutes) was increased, which was chosen as the optimized condition for the degradation of MB dye.

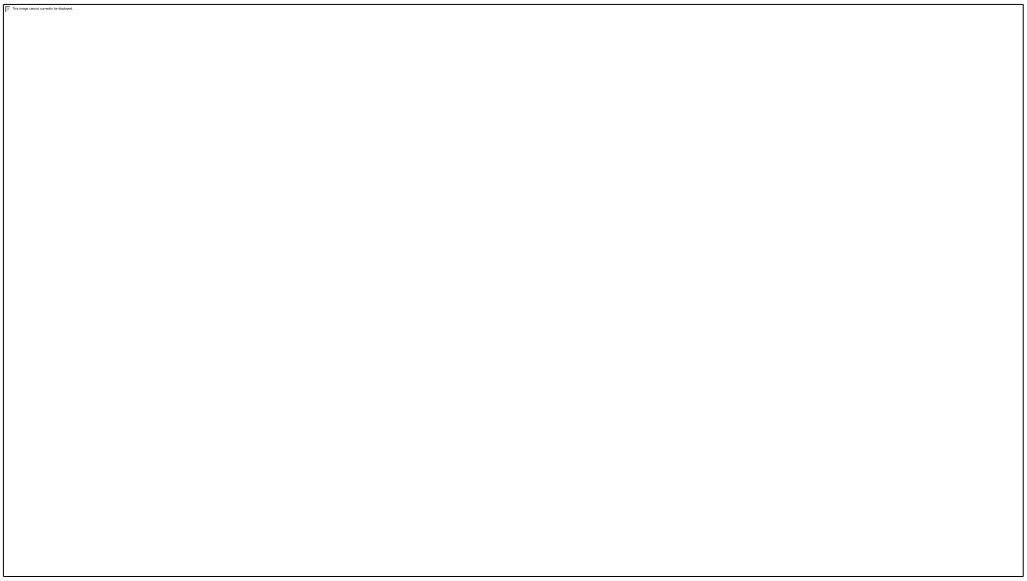

Figure. 4.6 PCD efficiency of Co_3O_4 nanoparticles.

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Discussion

The present investigation showed that the biological synthesis is an effective method for the environmentally friendly production of highly crystalline Co_3O_4 nanoparticles and excellent photocatalytic activity. The combination of characterization techniques confirmed that the synthesized nanoparticles had a desirable structural, morphological, elemental and optical parameters that collectively helped to increase the catalytic activity of the synthesized nanoparticles.

The XRD results confirmed the successful reduction and crystallization of the cobalt ions and showed that there were no secondary phases present with the formation of a pure cubic spinel phase Co_3O_4. The calculated crystallite size of about 19.29 nm is in good agreement with previous reports which showed that nanoscale crystallites possess much larger surface areas compared to bulk materials, thus providing a much higher number of catalytically active sites for photocatalytic reactions.

SEM images showed mostly spherical nanoparticles that appeared to be slightly aggregated. This phenomenon of agglomeration is often seen in metal oxide nM because of strong van der Waals interaction and high surface energy. However, the particle morphology was still fairly uniform to guarantee the efficient adsorption of the dye molecule, and the interaction between the catalyst surface and the incident light. Rapid charge transfer and low electron–hole recombination are two factors that are closely related to the uniformity of the nanoscale morphology, which is well known to be important for photocatalytic efficiency.

The EDX analysis also proved the successful synthesis of chemically pure cobalt oxide nanoparticles. The absence of undesirable elemental impurities means that the bacterial metabolites not only acted as reducing agents, but also as good stabilizing agents in the formation of nanoparticles. This discovery is one of the main benefits of green synthesis compared to traditional chemical approaches that often involve the use of stabilizing chemicals that can result in contamination of the final product.

FTIR spectroscopy was also used to confirm the formation of nanoparticles, with the peaks characteristic of Co–O stretching vibrations observed. Moreover, the hydroxyl and other oxygen containing functional groups indicate that the biomolecules that may have been metabolites of the bacteria were still attached to the surface of the nanoparticles. They can be used for stabilizing the nanoparticles and increasing the binding of dye molecules during the photocatalysis.

The Co_3O_4 nanoparticles prepared from the synthesis showed strong absorption in the visible spectrum based on the optical band gap energy values obtained from the diffuse reflectance spectra. The relatively small band gap makes it easier to promote electrons when it is exposed under light irradiation leading to the generation of Reactive Oxygen Species, which degrades the dye. The simultaneous presence of Co^{2+} and Co^{3+} ions in the spinel structure further enhances the charge transfer process which in turn decreases the chances of electron–hole recombination and thus increases the photocatalytic efficiency.

The photocatalytic degradation efficiency of the biosynthesized nanoparticles was found to be around 94.61%, which shows the remarkable catalytic ability of these biosynthesized nanoparticles. The synergistic effects of several physicochemical properties: high crystallinity, nanoscale crystallite size, good optical properties, spherical morphology, and high elemental purity are responsible for this high degradation efficiency. The findings indicate that biological synthesis is a promising method for the preparation of Co_3O_4 nanoparticles that not only have

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photocatalytic properties similar to or superior to those of many materials prepared using conventional methods, but also decrease the impact on the environment, the cost of production and chemical waste.

In conclusion, the present results are in line with the increasing evidence showing that green nanotechnology is a viable option to create sustainable photocatalysts that can combat environmental pollution. The highly efficient synthesis of Co_3O_4 nanoparticles offers an eco-friendly alternative for the treatment of waste water and paves the way for future research on the use of visible light photocatalysis, use of reusable catalysts, and large-scale use in the environment.

Conclusion

The study was a success in synthesizing the cobalt oxide (Co_3O_4) nanoparticles using the bacterial metabolites in an eco-friendly and sustainable process. The successful formation of highly crystalline cubic spinel Co_3O_4 nanoparticles with an average crystallite size of ~19.29 nm was confirmed by comprehensive physicochemical characterisation. SEM analysis showed mostly spherical nanoparticles and EDX analysis showed high elemental purity of cobalt and oxygen. FTIR spectroscopy confirmed the characteristic cobalt–oxygen bonds and diffuse reflectance spectroscopy showed good optical band-gap energies ideal for photocatalytic applications.

The synthesized nanoparticles obtained from the bio source had excellent photocatalytic activity and were found to degrade MB dye by around 94.61% after UV exposure. The high photocatalytic performance of their combination can be explained by the following factors: high crystallinity, nanoscale particle size, good optical properties and highly efficient charge separation. It is found that the biological synthesis method can produce excellent catalytic property nanomaterials and at the same time is simple, economical and environmentally friendly.

The study's findings are significant for sustainable nanotechnology as it showcases the use of biosynthesized Co_3O_4 nanoparticles for wastewater treatment and environmental remediation. Future research will focus on reusability of the catalyst, degradation mechanisms, the efficiency of the mineralization process, and the performance under the illumination of visible light, to assess their possible use in large-scale environmental treatment systems.

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